

S. Development of Titanium Component Applications in Heavy-Duty Diesel Engines

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Objectives

- Develop and demonstrate a high-strength, lightweight titanium aluminide (TiAl) turbine for a heavy-duty diesel engine. The unique material properties of TiAl will enable the next generation of turbocharger designs to have
 - improved thermal efficiency, and
 - increased transient response.

Approach

- Select the appropriate TiAl compounds and procure high-quality TiAl castings/forgings.
- Develop robust TiAl joining technology to deliver prototype TiAl turbine assemblies for engine testing.
- Demonstrate improved thermal efficiency and transient response in engine test.
- Establish a TiAl material property database to be used as a design tool and for improving next-generation TiAl turbine design.

Accomplishments

- Demonstrated joining of TiAl turbine wheel to Ti-6Al-4V shaft.
- Demonstrated joining of TiAl specimens to steel shaft material.
- Completed foreign object damage (FOD) testing.
- Evaluated physical and mechanical properties of candidate TiAl compounds.
- Assessed the commercial viability of using titanium alloys for turbocharger applications for heavy-duty diesel engines.

Future Direction

- Contract end September 30, 2005
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Introduction

Turbochargers on diesel engines play an integral role in enhancing engine performance, controlling fuel economy, and meeting emission regulations. After a half century of development, the performance of a turbocharger is now greatly limited by the properties of turbine materials. Turbines in diesel engines, subjected to long-term exposure to high-temperature exhaust gases above 750°C, are traditionally made of nickel-based superalloys. These superalloys have a relatively low specific strength and large inertia due to their high density, approximately 8.0 g/cm³. Therefore, turbines made of superalloys usually utilize a low air efficiency design and inherently have a slow transient response. A lightweight, high-strength, heat-resistant material to replace the current turbine materials is critical for further improving turbocharger performance.

Caterpillar has selected candidate TiAl intermetallic compounds to enable next-generation turbocharger designs. The candidate TiAl compounds possess a favorable combination of low-density and attractive high-temperature capabilities. Turbines made of TiAl compounds are anticipated to provide faster response (with reduced transient emissions) and better fuel economy. One of these turbine designs has already been chosen as the prime path for select Caterpillar off-highway applications in 2008. Experience with low-volume product under harsh conditions will also encourage high-volume applications aligned to Caterpillar ACERT™ engines for on-highway trucks in 2010.

Approach

The primary focus of the TiAl turbocharger project in the year 2005 is to develop technology to join TiAl turbine wheel to shaft materials. The difference between a TiAl turbocharger and a conventional one is the material used for the turbine wheel. In the 2004 budget year, Caterpillar identified two potential suppliers along with the candidate TiAl alloys and procured good quality cast TiAl wheels. Subsequently, the most important technology in manufacturing TiAl turbochargers is now the joining of the turbine wheel to its shaft.

Similar to other intermetallic compounds, limited ductility at ambient temperature of TiAl compounds intrinsically presents a great technical challenge for joining TiAl turbine to its shaft. Friction

welding (FW) was selected as a prime path for the joining because of previous success in joining TiAl valves to Ti6Al4V shafts in a Department of Energy (DOE)-funded project. However, weak and cracked joints with strengths of approximately 50 MPa were produced when the welding was scaled up from valve to turbine. A parametric study to conduct FW at different conditions could not avoid cracking, which typically occurred at the later stage of FW process. Therefore, two approaches have been pursued for the joining in this year. One is to continue the effort in friction welding to solve the cracking problem and achieve acceptable joint strength. Another is to examine brazing methods.

Once the turbine wheel is successfully joined to the turbine assembly with acceptable strength, a gas stand test will be completed for preliminary turbo efficiency and reliability. Subsequently, engine and machine tests will be conducted for demonstrating improved thermal efficiency and transient response. Material property characterizations have been conducted in parallel to the turbine rig tests to establish a TiAl materials database to be used as a design tool for improving next-generation TiAl turbine designs.

Results

Successful FW was accomplished to join TiAl turbine wheels to Ti6Al4V shafts. The successful welding was achieved through extensive finite-element analysis (FEA) simulations, aimed at understanding the correlation among the welding parameters, and intensive welding trials, designed according to the input acquired from the FEA simulations and microstructure characterization. The ultimate tensile strength of the joints between TiAl turbines and Ti6Al4V shafts has achieved 570 MPa.

The FEA simulations results confirmed the extremely high thermal stresses inside the TiAl turbine near the welding interface. The FEA simulations were conducted using commercial simulation tools and customized user subroutines based on a thermal mechanical model. Welding parts geometry and welding parameters were input to the simulation. Temperature profile, stress components, and strain components (deformation) were output from the simulation (an example is shown in Figure 1). Simulations using the conditions for the early FW trials showed that the hoop stresses near the welding line were more than 1 GPa. The simulation result agreed with the failure analysis work conducted at

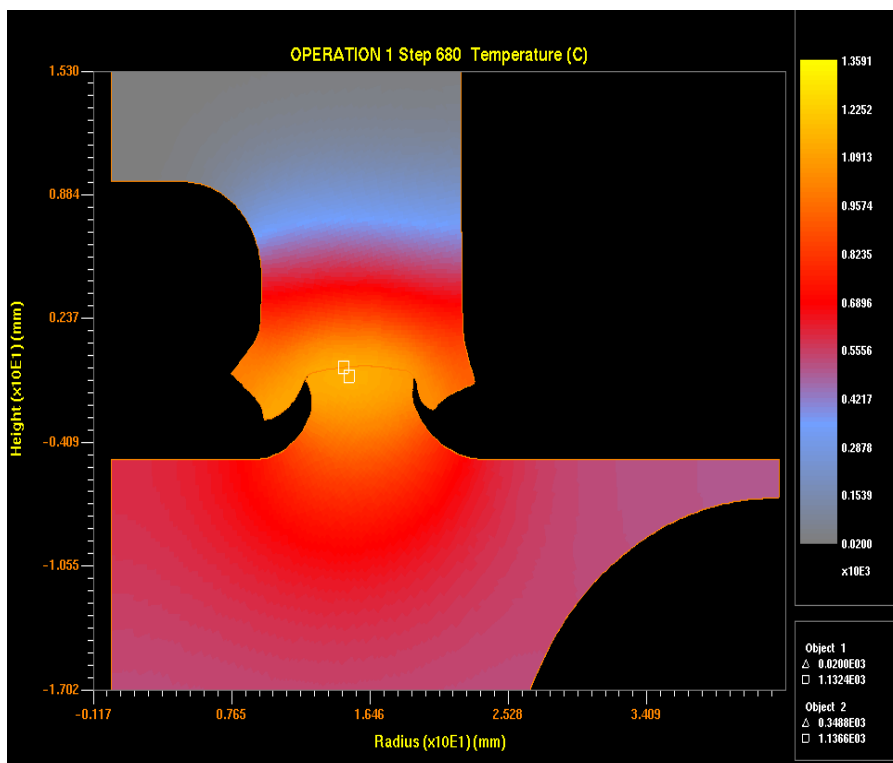


Figure 1. A temperature profile at the beginning of the forging stage obtained through simulations using a thermal mechanical model. FEA of the joining process is used to understand the sensitivity of the thermal stresses to FW control parameters. The simulations were carried out for the friction and forging stages, respectively, for the welding process.

cracked joints. Excessive thermal stresses were therefore identified as the primary cause for the joint cracking.

The critical factors determining the thermal stresses were then identified through FEA sensitivity studies. These simulations were performed using a systematic combination of the factors affecting FW process, including part geometry, rotational speed, friction and forge loads, and friction and forge times. Analyses were then conducted on the simulation results to provide a general understanding of the effect of these factors on the resulting temperature profile and thermal stresses. Among these factors, welding part geometries were relatively independent to other factors and were therefore optimized separately to minimize their effect on thermal stresses (Figure 2). Optimizing other critical factors was completed through intensive experimental trials. These experiments have been designed based on the understanding gained from the FEA simulations. Modification of the friction welding facilities has been implemented to conduct the design of experiments.

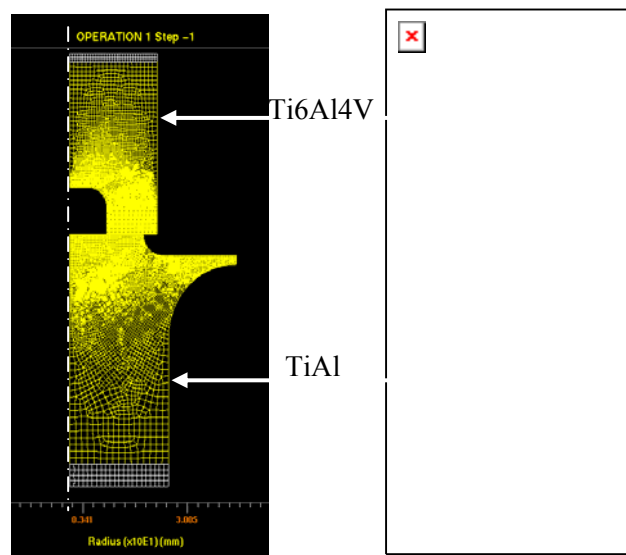


Figure 2. FEA used to study the effect of geometry constraint on the joint quality.

With the above efforts, the thermal stress cracking issue has been resolved and crack-free welding has been achieved. Figure 3 is a

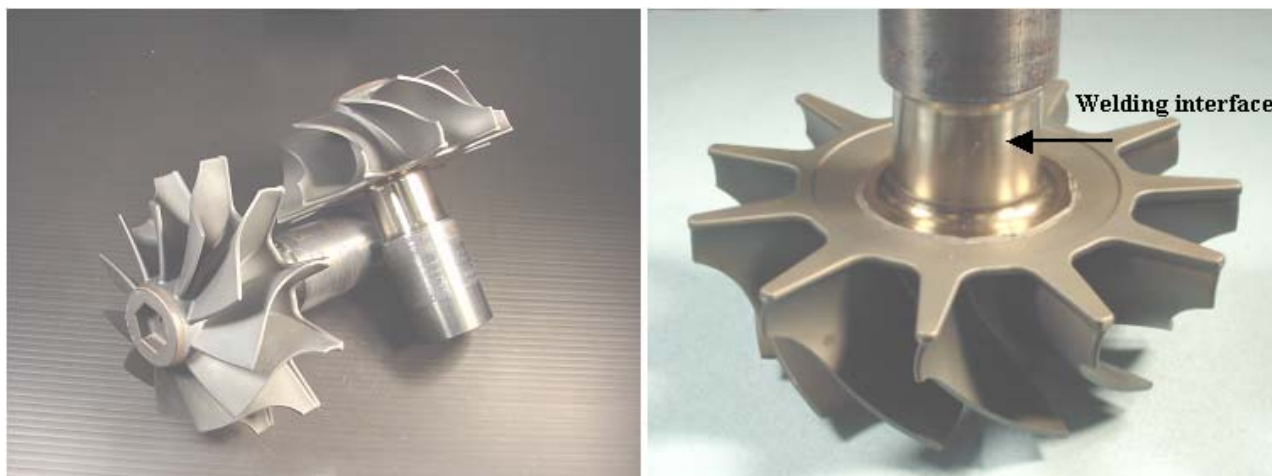


Figure 3. TiAl turbine wheels joined to Ti-6Al-4V shafts by FW.

representative photograph of these joined TiAl turbines (~1 kg). Nondestructive evaluation (NDE) techniques have been used in examining the weld joints. No crack or defect could be identified in the welding zone or heat affected zone. Figure 4 shows

several representative NDE scans obtained with Eddy current and ultrasonic inspection techniques. These scans could not capture any surface/subsurface cracks or radial cracks, but rather demonstrate the uniform weld interface. Compared to the

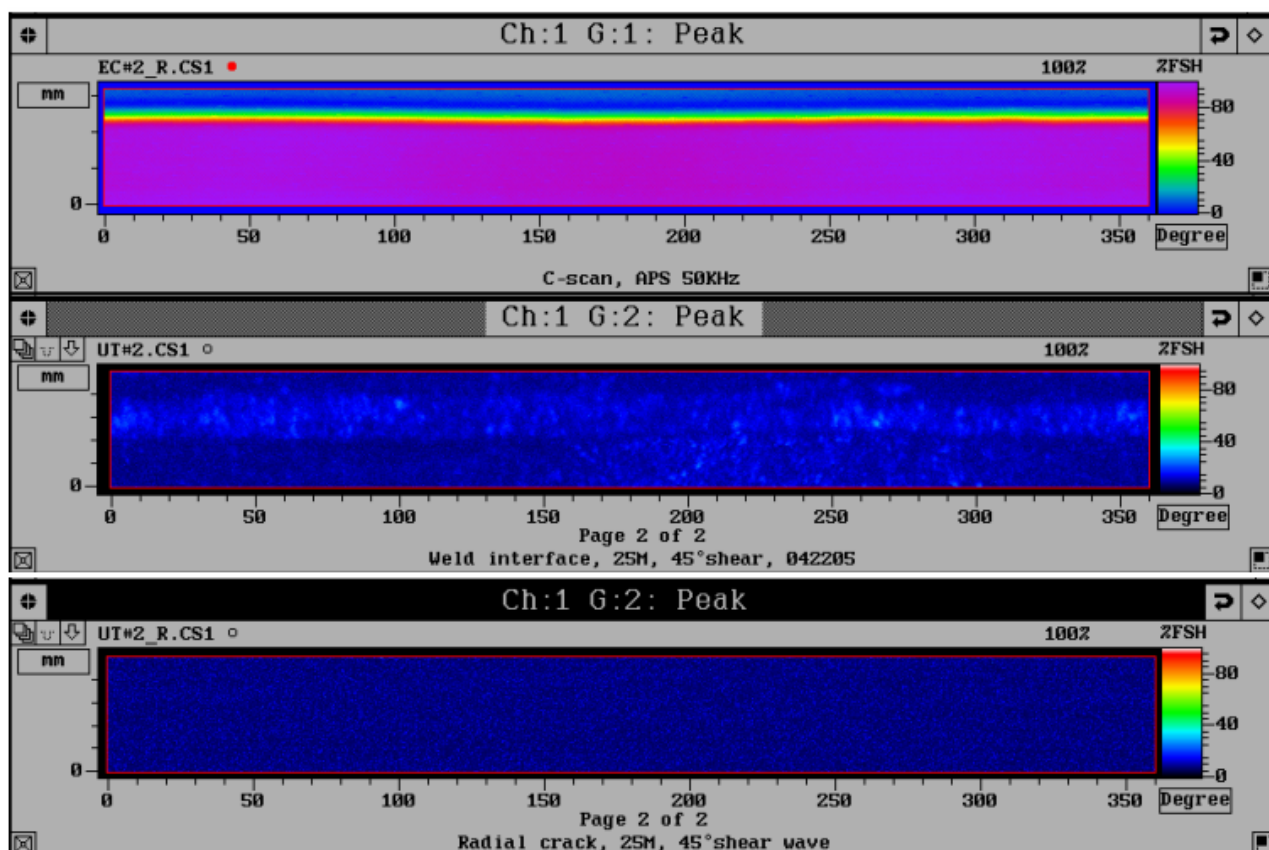


Figure 4. NDE results at the weld and heat affected zone. No surface or near surface cracks could be detected using (a) Eddy current technique, (b) ultrasonic inspections also indicate that the welding interface is uniform, and (c) free of radial cracks.

NDE results in the previous year annual report, the current NDE results indicated a significant improvement in joint quality. Tensile bars prepared from these welded joints demonstrated that the highest tensile strength was about 570 MPa. These tensile test bars usually failed several millimeters away from the welding interface in the TiAl turbine wheel side. In a full-scale tensile test on the turbine wheel, the fracture surface is about 20 mm away from the joint interface as shown in Figure 5. The joint strength has reached the strength of the TiAl alloy. The FW process has been further scaled up to larger size TiAl turbine wheels (~2 kg). Joints have been successfully produced free of any visual cracks. NDE examinations and tensile tests are yet to be completed on these joints.

Eighteen FW trials were conducted to join 50-mm-diam. Ti6Al4V bars to 37.5-mm-diam. 4140 steel bars with a goal to use steel instead of Ti6Al4V as a shaft material. Fifteen out of eighteen trials were successfully joined without any visual cracks. NDE examinations could not detect any cracks or defects in these joints. Mechanical tensile test have been conducted on tensile bars prepared from the

joints. The highest tensile strength is slightly more than 300 MPa, but the joints are rather brittle.

Materials characterizations have been carried out for the TiAl materials obtained from the two suppliers to compare the properties and establish a materials database to be used as a design tool for next-generation turbine applications. Mechanical tensile tests were performed at room and elevated temperatures for the TiAl materials from both suppliers. Figure 6 shows normalized results of ultimate tensile strength and elongation at failure for the two TiAl materials. Material from Supplier B has lower strength at low temperatures than Supplier A. However the curves cross over at about 700°C, above which the TiAl material from Supplier B becomes stronger than Supplier A. In addition, the ductility of the TiAl material from Supplier B is higher than that from Supplier A. Physical properties have also been measured, and the results show that the density of the TiAl materials from Supplier A is about 2% higher than that of Supplier B. Thermo-physical properties of the two TiAl materials are apparently different. As shown in Figure 7, thermal conductivity of the TiAl material from Supplier B is

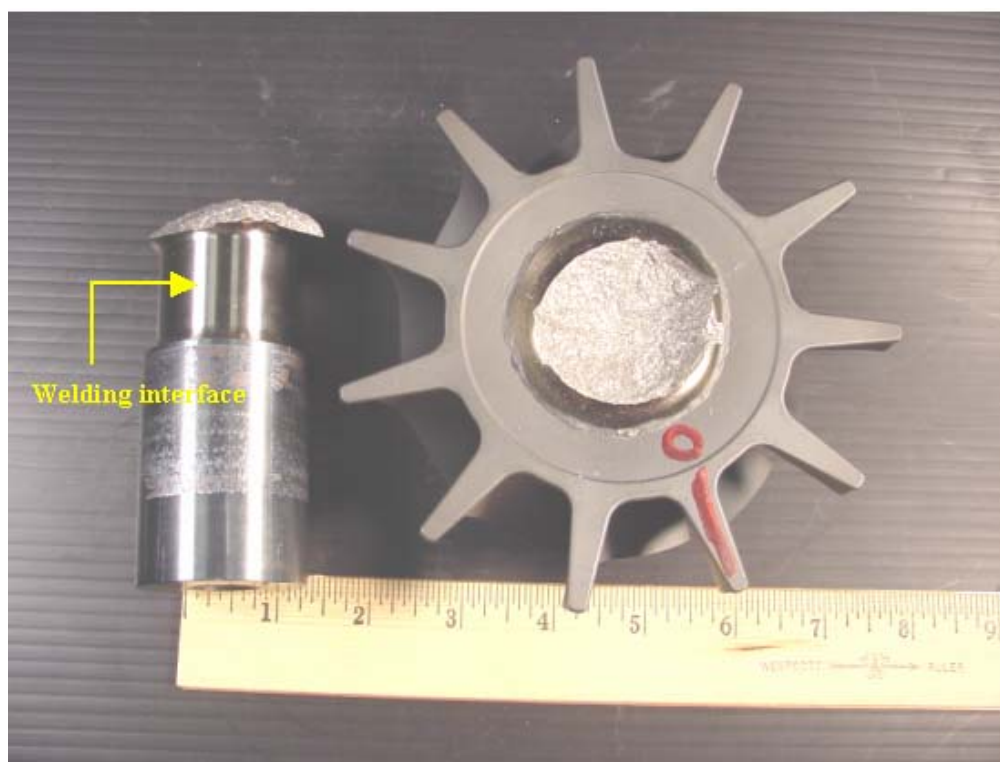


Figure 5. Friction-welded TiAl turbine wheel failed about 20 mm away from the FW interface in mechanical tensile test. The hub of TiAl turbine wheel is completely pulled out of TiAl wheel.

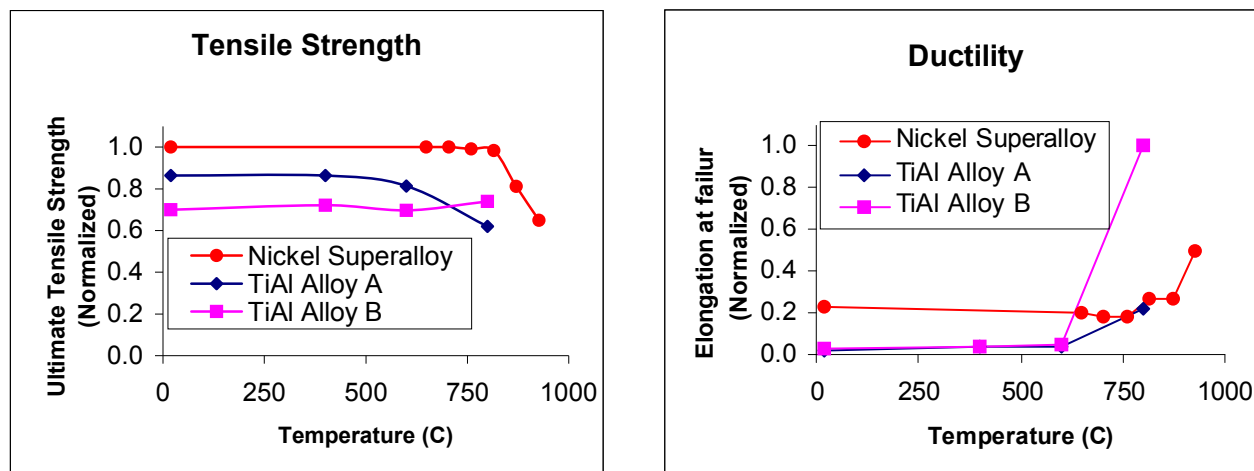


Figure 6. Comparison of tensile strength and ductility of TiAl compounds and nickel-based alloy.

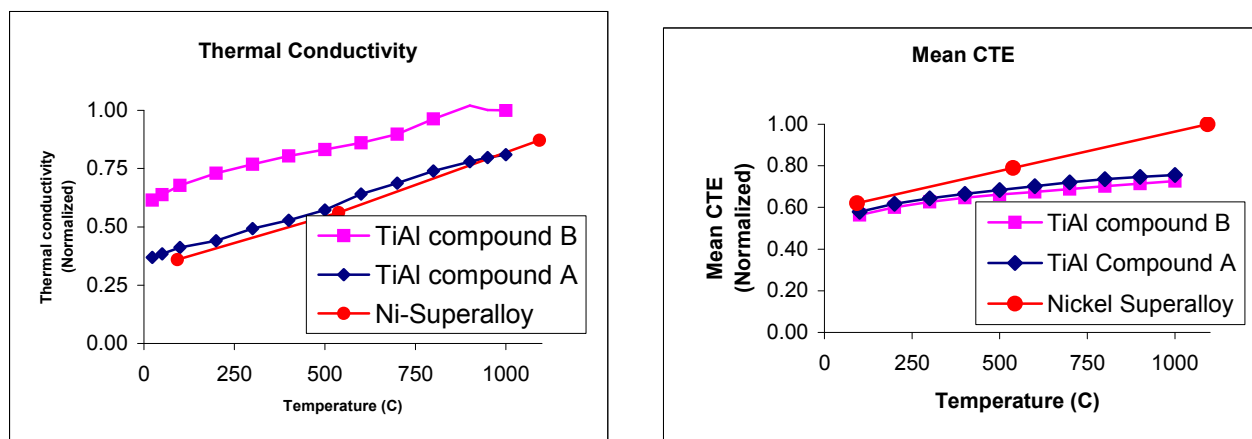


Figure 7. Comparison of thermal conductivity and coefficient of thermal expansion for TiAl compounds and nickel-based alloy.

more than 30% higher than that from Supplier A, but the coefficient of thermal expansion of the TiAl material from Supplier B is about 5% less than that of the material from Supplier A.

FEA simulations have been conducted to evaluate the effect of material property differences of the two TiAl alloys in the turbocharger applications. This involved the analysis of the strain/stress differences in the turbine at engine operating conditions based on the measured properties data. Consequently, no significant effect could be found despite the discrepancies in properties of the two TiAl materials. Creep tests are being conducted at Oak Ridge National Laboratory (ORNL) as well as an external

test facility. These tests are scheduled to be completed by the end of 2005. Low-cycle fatigue (LCF) tests will start in the next quarter and be followed with full-scale thermal mechanical fatigue (TMF) tests.

Conclusions

Successful FW has been achieved in joining ~1-kg TiAl turbines to Ti6Al4V shaft. The joint tensile strength has been increased more than tenfold from ~50 MPa to 570 MPa. The FW process is yet to be fully scaled up to a ~2-kg TiAl turbine wheel. Sufficient confidence has already been gained in FW TiAl turbine wheels to Ti6Al4V shafts. Validating

the joint quality needs to be completed before a gas stand or engine test on these turbines to demonstrate improved transient response and thermal efficiency. The option of using steel shaft through FW joining is still dubious. The tensile strength of the joints produced between 4140 steel and Ti6Al4V shafts is about 300 MPa, lower than the tensile strength of TiAl material. Microstructure characterization needs to be conducted to investigate the brittleness of these joints.

Mechanical tensile tests, physical properties characterizations and FEA simulations have been carried out for the TiAl materials from the two suppliers. No significant differences in terms of turbine

applications have been identified for the two TiAl materials despite some discrepancy in their mechanical and thermophysical properties. Characterizations for creep properties and thermomechanical fatigue properties of the two TiAl materials are yet to be completed.

Presentations and Publications

Presented for a DOE annual program review on April 27, 2005.

Poster for DOE Heavy Vehicle Propulsion Materials Merit Review, September 12–16, 2005.

